NASA TTF-10,378

THE EFFECT OF THERMAL TREATMENT ON THE PHOTOELECTRIC PROPERTIES OF SILICON HAVING STRUCTURAL MODIFICATIONS DUE TO RADIATION

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Translation of "Issledovaniye vliyaniya temperaturnoy obrabotki na fotoelektricheskiye svoystva kremniya, soderzhashchego radiatsionnyye narusheniya struktury". Doklady Akademii Nauk BSSR, Vol. X, No. 3, pp. 148-150, 1966.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. OCTOBER 1966

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ABSTRACT

The thermal stability of silicon monocrystals irradiated with high energy particles is investigated. *p*-type silicon with a specific resistance of 7-100 ohm·cm and containing oxygen in a concentration of 3 - 8.10^{17} cm^{-3} was bombarded with 1 MeV electrons.

The purpose of this article is to study the thermal stability of different radiation modifications which are produced in monocrystals of silicon when they are irradiated with high energy particles. It may be concluded from several articles (Ref. 1-3) that defects of one type may change into defects of another type, due to the combination of structural modifications caused by radiation at different points (vacancies, interstitial atoms) with different residual chemical admixtures. However, up to the present time there has been hardly any research devoted to a study of the kinetics of the formation of radiation modifications in silicon. /148*

p-type silicon with a specific resistance of 7 - 100 ohm·cm, containing oxygen in a concentration of 3 - $8\cdot10^{17}$ cm^{-3}, was employed as the initial material. Irradiation was performed with electrons having an energy of about 1 Mev at temperatures of 80°K and 30° in an electrostatic generator. The samples were irradiated at low temperatures directly in a cryostat, which made it possible to measure the photoconductivity spectra without heating the samples. The spectral dependences of the stationary photoconductivity were recorded on an apparatus which was described in (Ref. 4).

Figure 1 presents several spectral dependences of the photoconductivity signal in the 1-13 micron range for a *p*-type sample with an

* Numbers in the margin indicate pagination in the original foreign text.

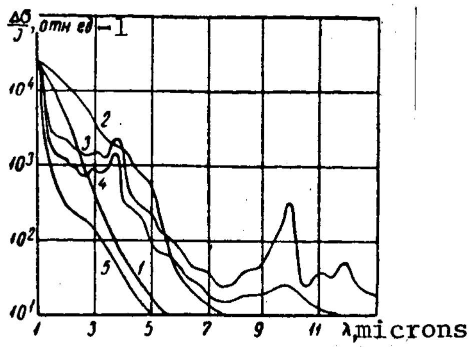

Figure 1

Photoconductivity Spectra of *p*-type Silicon Irradiated
by Rapid Electrons at $T = 80^{\circ}K$
1 - Rel. Units

initial specific resistance of 98 ohm·cm, which was irradiated by a stream of electrons of $5 \cdot 10^{16}$ cm^{-2} at a temperature of $80^{\circ}K$. Curve 1 was obtained one hour after the irradiation had stopped. It did not indicate any structural (modification): The signal increased smoothly with a decrease in the wavelength of the exciting radiation. Curve 2 shows a spectrum of the same sample, after it was stored for five hours at the temperature of liquid nitrogen. It may be seen that a structure appeared on the curve which was observed previously (Ref. 3) when crystals were irradiated at room temperature by streams of 10^{17} electrons/cm^2 and greater. Curve 3 was recorded after the sample was stored for 20 days at room temperature; curve 4 -- after the sample was annealed at a temperature of $200^{\circ}C$ for 20 minutes; and curve 5 -- after it was annealed at a temperature of $400^{\circ}C$ for 20 minutes.

An analysis of curve 1 shows that the vacancy-interstitial atom pairs formed during the irradiation process (there is very little possibility that association will be produced at the temperature of liquid nitrogen due to the small diffusion rate) have considerable photoconductivity in the wavelength region which is shorter than 3.0 microns. This pattern of the curve may be explained as follows. Immediately after the irradiation, the photoconductivity is primarily determined by point structural modifications, i.e., by vacancy-interstitial atom pairs which are located at different distances from each other. These centers have energy levels which are primarily located close to the zone edges. /149
Curve 1 clearly represents the considerable photoconductivity in the region of wavelengths corresponding to the ejection of electrons from the valent zone at the levels of these centers. There are no steps in this portion of the spectrum, since the irradiation leads to the formation of pairs with different distribution. The energy spectrum for the binding

energy of an electron with these pairs must be continuous or discrete with a large set of levels.

Curve 2 shows that even at a temperature of 80°K diffusion of Frenkel pair members occurs. In the diffusion process they are captured by admixture atoms or other crystal imperfections, or they destroy each other. When the Frenkel pair members are captured by admixture atoms, associations are produced which determine the spectrum of the photoconductivity signal for crystals irradiated at room temperatures. In the case of irradiation at low temperatures, the slow formation of such associations indicates that the processes by which stable structural modifications are produced include diffusion of interstitial atoms and vacancies in the crystal. The quantitative studies of the processes by which defects are produced are complicated by the fact that even at nitrogen temperatures annealing occurs (destruction) of the point defects produced by the irradiation.

Curve 3, which was measured after the sample was stored at room temperature, actually shows that a temperature increase leads to the formation of new radiation modifications which determine the photosensitivity of the material in the long wave portion of the spectrum. There is a relative increase in photoconductivity in the long wavelength region, and a decrease in the short wavelength region. It may be seen from an analysis of curve 3 that the irradiation of silicon crystals at low temperatures leads to the formation of many radiation modifications which introduce extensive energy levels into the forbidden zone (E_v + 0.12 ev, E_v + 0.18 ev, E_v + 0.21 ev, E_v + 0.24 ev, E_v + 0.30 ev, E_v + 0.35 ev, E_v + 0.38 ev, E_v + 0.45 ev, E_v + 0.49 ev, and E_v + 0.55 ev).

An analysis of curves 4 and 5, obtained after the crystals were annealed, makes it possible to draw several conclusions regarding the temperature stability of the centers observed.

Thus, if the crystal is heated for 20 minutes at a temperature of 200°C, this leads to a great decrease in the concentration of centers introducing levels which are located comparatively close to the valent zone (E_v + 0.12 ev, E_v + 0.18 ev, E_v + 0.21 ev). The concentration of centers introducing the levels E_v + 0.30 ev, E_v + 0.35 ev, E_v + 0.45 ev, and E_v + 0.49 ev, barely changes. Temperatures greater than 400°C are necessary in order to break up the centers introducing these levels, which is confirmed by the results shown in curve 5. The centers E_v + 0.30 ev and E_v + 0.45 ev are entirely annealed only when the crystals are heated up to temperatures greater than 500°C for several hours. Since the E_v + 0.30 ev center is apparently related to the association of oxygen atoms with interstitial atoms of silicon, we may reach the conclusion that oxygen produces the most stable associations with point structural defects.

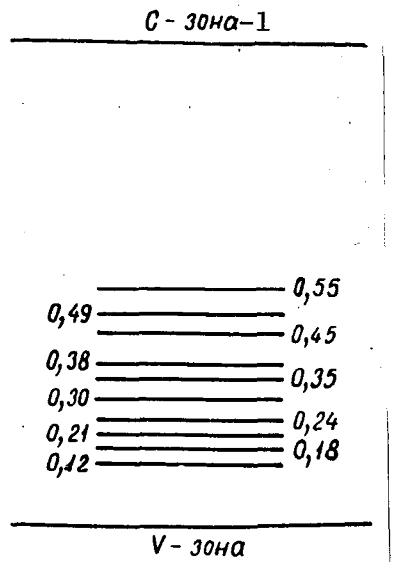

Figure 2

Diagram Showing the Positions of Energy Levels of Defects Produced in p-type Silicon After Irradiation by Rapid Electrons

1 - Zone

Unfortunately, due to the extremely complex nature of the processes by which radiation modifications are annealed, we have not yet been able to obtain more precise quantitative characteristics for these defects. Basic difficulties arise due to the large number of different types of structural defects, which may change into each other during the annealing process. Figure 2 presents an idea of the complexity of the energy spectrum of radiation modifications in p-type silicon. This figure presents the energy positions of all centers which are produced during irradiation by electrons and which are stable at room temperature.

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Received June 14, 1965

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